Soils and Foundations 2012;52(4):590–599

The Japanese Geotechnical Society

Soils and Foundations

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# Use of fall cone test as measurement of shear strength for soft clay materials

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Received 13 November 2011; received in revised form 3 April 2012; accepted 1 May 2012
Available online 11 September 2012

**Abstract**

A fall cone test (FCT) was carried out to obtain the undrained shear strength ($s_u$), and to measure the sensitivity ($S_t$) of intact and remolded samples from several sites in Japan. The value of $s_u$ from FCT was compared with half of the unconfined compression strength ($q_u/2$), which is a standard way to evaluate $s_u$ for practical design in Japan. It is found that $s_u$ from FCT is neither related with $q_u/2$ nor used directly as a design value. $S_t$ was also obtained by field and laboratory vane tests. A comparison study revealed that $S_t$ by FCT is as much as 10 times larger than that by the field vane. The large difference in $S_t$ measured by different testing methods can be attributed to remolding methods. That is, the remold condition for FCT was created by kneading the sample in a plastic bag by hand, while in the field vane, the ground was remolded by 30 turns of the vane blade. This indicates that the degree of the reduction in strength caused by the turn of the vane blade is less significant than that caused by remolding by kneading.


*Keywords:* Fall cone test; Sensitivity; Remolded strength; Undrained shear strength; Liquid limit (IGC: C6)

## 1. Introduction

The fall cone test (FCT) is a simple testing method in which a cone is penetrated into a soil specimen by its self weight and the penetration depth is measured. This test is extensively used for measuring Atterberg limits, i.e., liquid limit ($w_L$) and plastic limit ($w_P$), undrained shear strength ($s_u$) for intact as well as remolded clay sample and to determine sensitivity ($S_t$). On the other hand, Japan has been very conservative about the use of the FCT, and decided in 1997 to use it only to measure the liquid limit ($w_L$) (The Japanese Geotechnical Society, JGS standard 0142-2000). However, $w_L$ is in most cases still measured by the Casagrande method, i.e., using a cup.

Japan is one of only a few countries where the $s_u$ design value is determined only by the unconfined compression test (UCT) (Tanaka, 2000). The theoretical background for the validity of a half of the unconfined compression strength ($q_u/2$) as the mobilized undrained shear strength ($s_{um}$) has been studied by many researchers, such as Ohta et al. (1985), Tsuchida (2000) and Tanaka (2002a,2002b). According to their studies, $q_u/2$ is a suitable value that balances the under- and over-evaluating factors well to indicate true strength, such as sample disturbance, anisotropy and the rate effects. In other countries, however, the UCT is considered a less reliable test for obtaining $s_{um}$. Indeed, the Eurocode 7 describes the UCT as an index test with the same rank of the FCT.

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Peer review under responsibility of The Japanese Geotechnical Society.

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http://dx.doi.org/10.1016/j.sandf.2012.07.002

$S_t$ is a very important parameter in geotechnical engineering, especially in practical construction works, i.e., to evaluate trafficability or workability. $S_t$ used to be measured in Japan by the UCT, in which the $q_u$ value is measured for intact and remold conditions and $S_t$ was defined as a ratio of these $q_u$ values. However, this article was eliminated in the standard of JGS in 1976, because it is very difficult to make a remolded specimen with highly sensitive samples because of their low strength, and for a very stiff sample, thoroughly remolding is very difficult. A testing method still in use for determining $S_t$ is the Field Vane Test (FVT) (JGS 1411-2003). In this standard, $S_t$ is defined as a strength ratio of undisturbed and disturbed strengths after more than 10 turns of the vane blade.

This paper will examine whether the strength measured by FCT is equivalent to the $q_u$ value measured by UCT, using the authors' data base accumulated from several sites in Japan. The remolded strength by FCT will be compared to that measured by the FVT and Laboratory Vane Test (LVT). Finally, $S_t$ will be compared with these different testing methods.

## 2. Testing methods

### 2.1. Fall cone test (FCT)

The FCT was carried out following the standard of JGS (JGS 0142-2009) for the measurement of $w_L$, i.e., the mass and the conical angle of the cone are 60 g and 60°, respectively. These values are the same as those in Canada and Scandinavian countries. After the tip of the cone touches the specimen surface, the cone was freely dropped. After 5 s, the penetration depth was measured by a dial gage. The $s_u$ was calculated by the following equation:

$$s_u = k_\alpha (mg/d^2) \tag{1}$$

where $m$ is mass of the cone (=60 g), $g$ is the earth gravity acceleration, $d$ is the penetration depth, and $k_\alpha$ is the cone factor depending on the cone angle. $k_\alpha = 0.29$ was adopted, according to Wood (1990) for the cone angle of 60° in this study.

Intact specimens for FCT were obtained by a soil sample extruded from a sampling tube and cut by a wire saw (thickness = approx. 40 mm). A cylindrical specimen was directly placed on the basement of the Fall Cone apparatus, and the penetration test was carried out at 5 different points of the same specimen, where each point was far enough from the previous penetration tests not to be influenced by disturbance. The represented value from FCT was adopted as the average values of three measured ones, omitting the maximum and minimum values. The remolded specimens were made as follows: soil fragments yielded from the trimming of specimens for other mechanical tests or soil samples after testing of UCT were put into a plastic bag and kneaded uniformly by hands for 5 min. The kneaded sample was then stuffed into a cup defined by the standard of liquid limit by the fall cone (JGS 0142-2009), i.e., its inside diameter and depth are more than 60 mm and 30 mm, respectively. The remolded strength ($S_{uFCT}$) was calculated from one penetration depth, because the measured value was not scattered unlike intact samples.

### 2.2. Unconfined compression test (UCT)

The UCT was also carried out, following the standard by the Japanese Industrial Standard (JIS A 1216:2009): the specimen was trimmed by a wire saw to a diameter and height of 35 and 80 mm, respectively. The specimen was compressed at a constant strain rate of 1%/min. The peak strength was defined as the unconfined compression strength ($q_u$).

### 2.3. Field vane test (FVT)

The testing method for the FVT mainly followed the JGS 1411-2003, using a penetration type without a borehole. The vane blade was 40 mm in diameter and 80 mm in height, respectively. To avoid damage the vane blade was protected by the sheath in the process of the penetration. When the device arrived at a testing depth, only the vane blade penetrated from the sheath into the ground. Then the blade was rotated at a rotation speed of 6°/min. After attaining the peak strength ($s_{uFVT}$), the vane was rotated a further 30 turns at a rapid rotation speed (about 5 s per a turn). Again the vane blade was rotated at the same rotation speed of 6°/min to obtain the remolded strength ($s_{uFVT30}$).

### 2.4. Laboratory vane test (LVT)

The LVT was also performed, using a smaller vane (the diameter and height were 20 mm and 40 mm, respectively) (Tanaka, 1994). For measuring undisturbed strength ($s_{uLVT}$), the vane was inserted into the soil sample kept in the sampling tube (the Japanese standard sampler, i.e., inside diameter = 75 mm). The remolded specimens were created by two methods. One is the same as the FVT, i.e., after attaining peak strength, the vane was rapidly rotated by 30 turns and the remolded strength ($s_{uLVT30}$) was measured by the rotation speed of 6°/min. Another remolded specimen was made by kneading soil samples in the same manner as the FCT. The remolded strength ($s_{urLVT}$) was measured by the LVT after the remolded sample was stuffed into a container.

### 2.5. Atterberg limits

Liquid and plastic limits ($w_L$ and $w_P$, respectively) were obtained by the Japanese Industrial Standard (JIS A1205: 2009), i.e., FCT was not used either for $w_L$ or $w_P$

## 3. Investigated sites

Samples and field data used in this study were obtained from the following sites: Atsuma, Takuhoku, Y-Ariake and H-Osaka. However, at the H-Osaka site, the FVT was not carried out, but only laboratory tests were done. The main geotechnical properties are shown in Fig. 1.

The Atsuma and Takuhoku sites are located in the Ishikari Plain, Hokkaido. The clay layer at both sites are mechanically normally consolidated, (no greater pressure than the present effective overburden pressure has ever been subjected to the investigated layer) and index properties, natural water content ($w_n$) and grade composition are very similar for both sites. The important characteristics for these sites are its relatively large variation in the $s_u$ ($=q_u/2$) at the Atsuma site, and the smaller $p_c$ value than the effective overburden pressure ($\sigma'_{vo}$) at the Takuhoku site.

Including these sites, soil samples at all sites in this study were retrieved by the Japanese standard sampler (Tanaka, 2000) and the drilling and sampling were carried out by the same single person who has the high skills necessary to get high quality samples. Thus, the variation in $q_u/2$ may not be attributed to the different sample quality, but probably reflected the natural properties. On the contrary, the reason

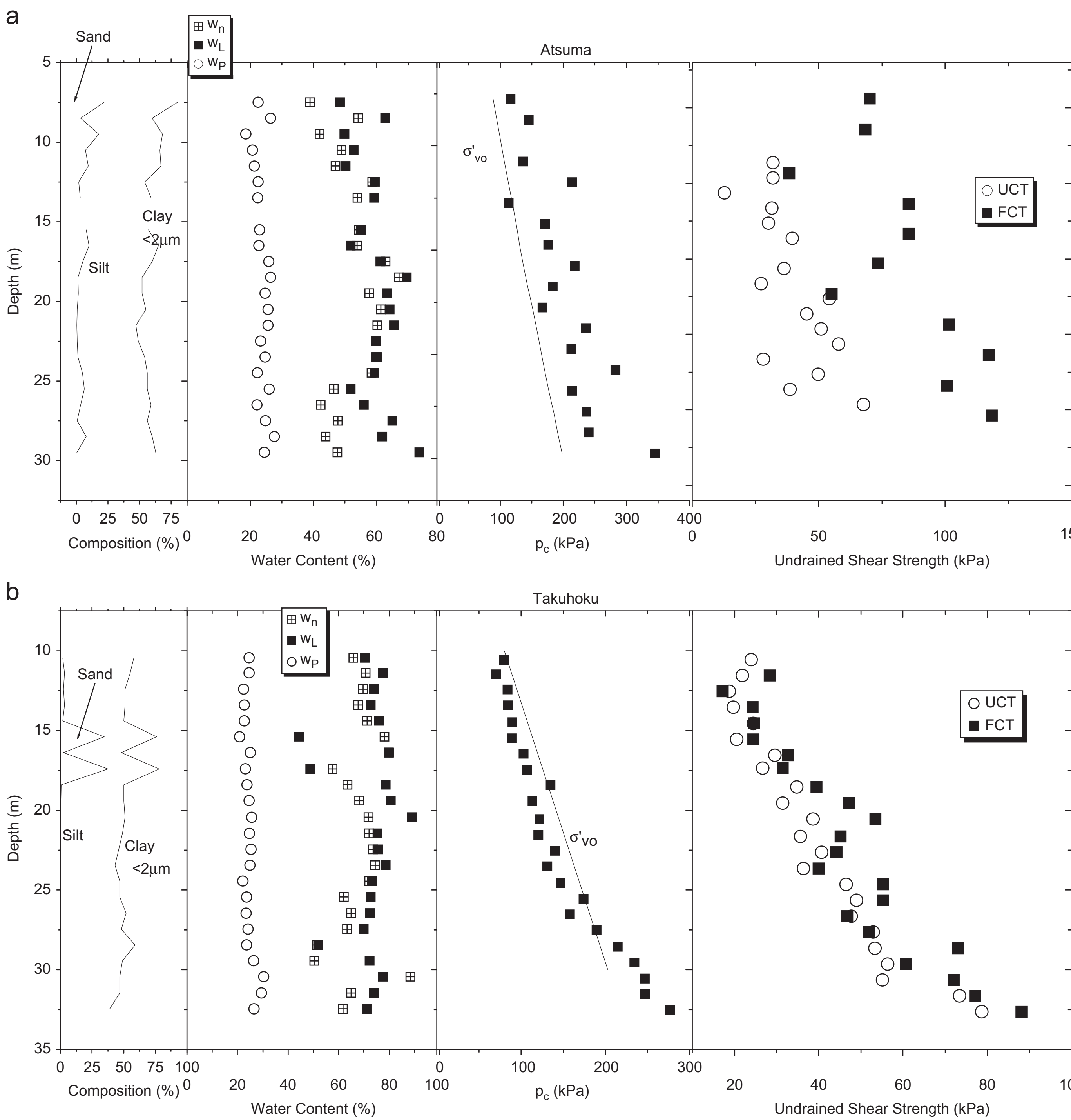



Fig. 1. Geotechnical properties of the investigated sites (a) Atsuma site, (b) Takuhoku site, (c) Y-Ariake site and (d) H-Osaka site.

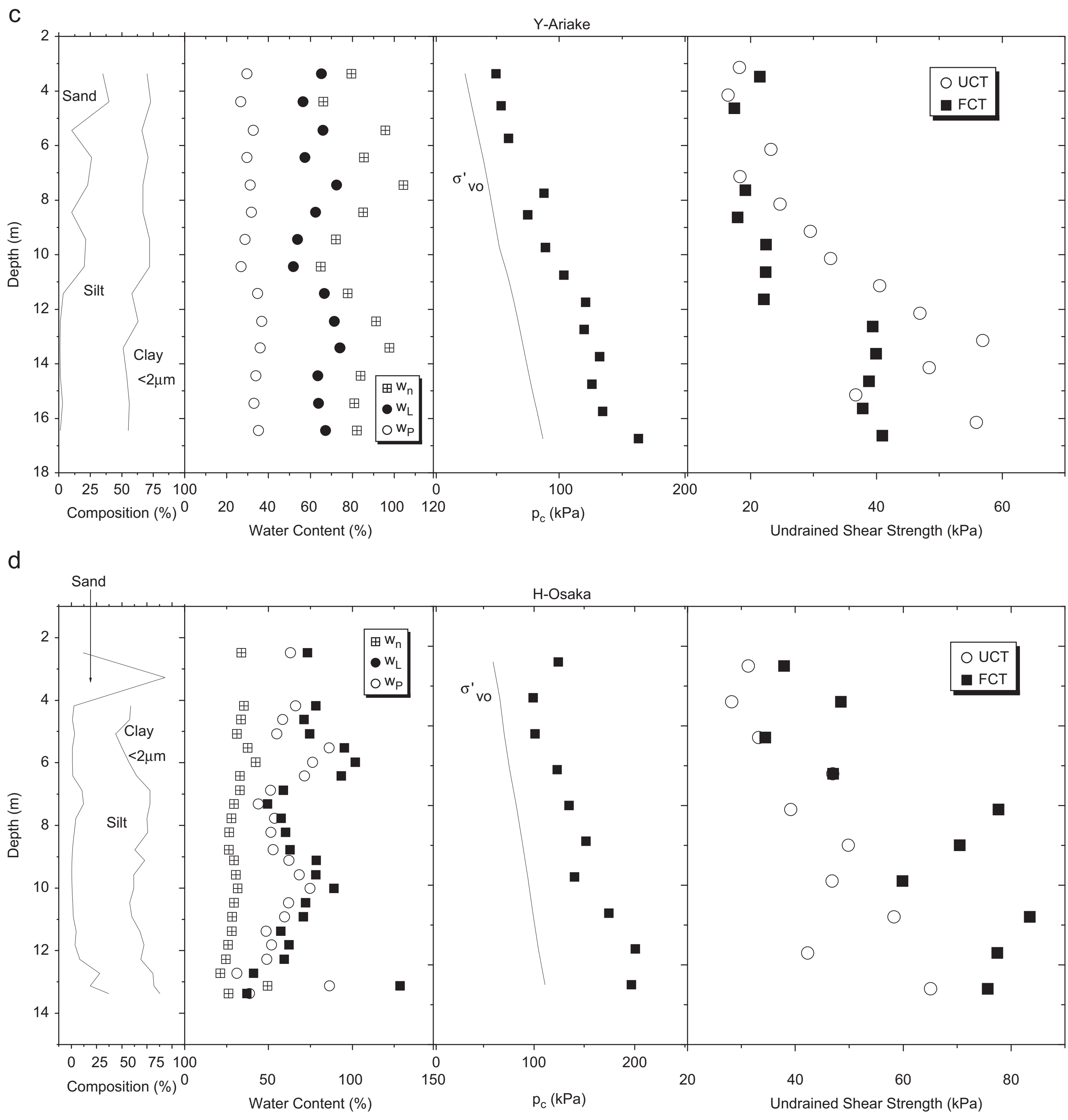



Fig. 1. Continued.

for the small $p_c$ at the Takuhoku site is clear: under consolidation. This site was filled relatively recently. The consolidation due to the fill has not yet finished. For more details of their characteristics, including the CPT data, please refer to Horng et al. (2010,2011).

The site of Y-Ariake is located at Hizen Kashima, Kyushu. This site is very close to the Arike Site, which is the site used by the authors to investigate soft clay (for example, Tanaka, 2000; Tanaka et al., 2001a). However, the properties at the present site is somewhat different from the Arike Site. In order to avoid confusion, the name of this site will be called "Y-Ariake", Y being the first letter of Yamaashi, the local name. The most prominent difference in the properties at this site is that $w_n$ is significantly larger than $w_L$, i.e., the liquidity index ($I_L$) significantly exceeds 1 (see Fig. 1(c)).

The formal name of H-Osaka is Higashi (East in Japanese) Osaka, where it is known that the high sensitive clay is distributed (for example, Oka et al., 1996). The site investigated by this study is located in Hanazono, Osaka prefecture. However, $I_L$ at the H-Osaka site is not so high as that at the Y-Ariake site, but similar to that at the Atsuma and Takuhoku sites. Although the index and $I_L$ properties are very different in the studied sites, the order of $s_u$ values to the depth is nearly the same for all sites, i.e., between 20 kPa and 70 kPa.

## 4. Comparison of strengths from UCT and FCT

The results of the comparison of the $q_u/2$ and $s_u$ values from FCT ($s_{uFCT}$) for each site, are given in the right figure of Fig. 1. These relations considerably vary according to the sites: the Takufoku site shows a very close relation with $q_u/2$ and $s_{uFCT}$, although the $s_{uFCT}$ values are clearly larger than $q_u/2$. A large scatter in the relation is observed at the Atsuma and H-Osaka sites and the $s_{uFCT}$ is significantly greater than $q_u/2$. On the other hand, the relation at the Y-Ariake is reversed from the other three sites: i.e., $s_{uFCT}$ is smaller than $q_u/2$.

Fig. 2 shows the direct comparison of $s_u$ obtained by UCT and FCT. Although large scatter can be recognized in this figure, a clear trend exists: $q_u/2$ is mostly smaller than $s_{uFCT}$ except for the Y-Ariake site. This tendency is also confirmed in Table 1, where S.D. is the Standard Deviation. The table indicates that the average ratio of $(q_u/2)/s_{uFCT}$ is 0.74 at the Atsuma and H-Osaka sites; 0.85 at the Takuhoku site and 1.20 at the Y-Ariake. The reason for the differences in the $(q_u/2)/s_{uFCT}$ ratios at each investigated site can be attributed to the sample quality. That is, if the sample quality more strongly affects the UCT strength than $s_{uFCT}$, then $(q_u/2)/s_{uFCT}$ would decrease with sample quality. Horng et al. (2011) investigated the effects of the sample quality on the undrained shear strengths using several samplers with different geometries, i.e., different wall thicknesses and cutting edges of the sampling tube. In their study, the undrained shear strengths were

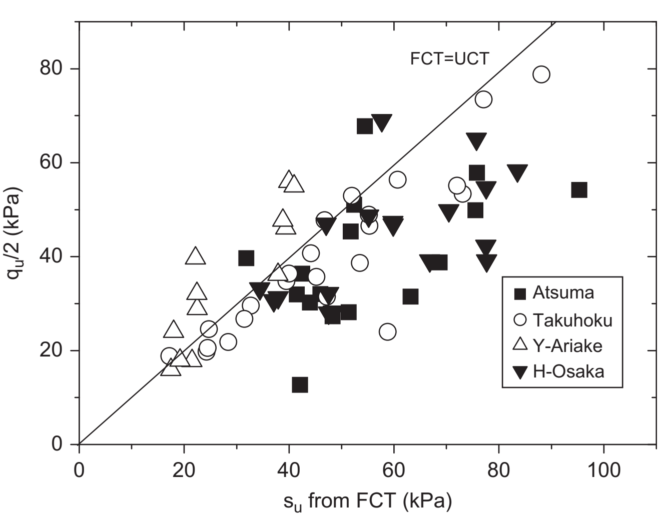



Fig. 2. Comparison of undrained shear strengths from UCT and FCT.

Table 1
Strength ratio of $(0.5q_u/s_{uFCT})$, where $0.5q_u$ and $s_{uFCT}$ are measured by UCT and FCT, respectively.

| Site | No. of samples | Mean | S.D. |
|---|---|---|---|
| Atsuma | 16 | 0.74 | 0.26 |
| Takuhoku | 22 | 0.85 | 0.14 |
| Y-Ariake | 11 | 1.20 | 0.28 |
| H-Osaka | 18 | 0.74 | 0.18 |

evaluated by UCT and FCT. They concluded that the effect of disturbance in the UCT is the same as that in the FCT: i.e., the FCT is also able to evaluate the sample quality. It should again be noted that the soil samples at all sites including Y-Ariake were retrieved by the same driller, so that their quality for every site can considered to be the same. Therefore, it cannot be concluded that a difference in sample quality at the Y-Ariake site caused the different ratio of $(q_u/2)/s_{uFCT}$.

Another reason for the different ratio of $(q_u/2)/s_{uFCT}$ measured in this study may have been the difference in soil properties, especially the order of $I_L$. As indicated in Fig. 1, the $I_L$ value in Y-Ariake is significantly greater than that at other sites. It can be seen in Fig. 3 that $(q_u/2)/s_{uFCT}$ apparently increases with $I_L$, in spite of the large scatter in this relation. At the Takuhoku and Y-Ariake sites, the undrained compression and extension strengths were obtained from the recompression method, where the specimen was consolidated under the in situ effective stresses (for the Takuhoku site, instead of these stresses, $0.8p_c$ values were adopted as consolidation pressures, since the targeted layer is not fully consolidated under the present burden pressure). For more detail, see Horng et al. (2011). Fig. 4 shows the strength ratios normalized by $s_{uFCT}$, where CUC and CUE are the compression and extension strength, respectively. Compared with strength ratios for the Takuhoku site, it can be seen that test results from the Y-Ariake site exhibit large variations, indicating that the strengths measured by various testing methods differ considerably, i.e., the strength anisotropy is prominent. It is interesting to note that the extension strength normalized by $s_{uFCT}$ is nearly the same for both Takuhoku and Y-Ariake sites. This implies that the extension strength has effects on $s_{uFCT}$ and the difference between these strengths may be due to the strain rate effect (Boukpeti et al., 2012). Although further research is required to confirm the above inference, it may be concluded from the present study that $s_u$ from FCT is not equivalent to $q_u/2$ value, at least not for Japanese clays, and cannot be used as the design value for evaluating the stability analysis.

## 5. Sensitivity

The results of a comparison of $S_t$ measured by different methods are given in Fig. 5, where the test result from the H-Osaska site is not presented because the FVT was not

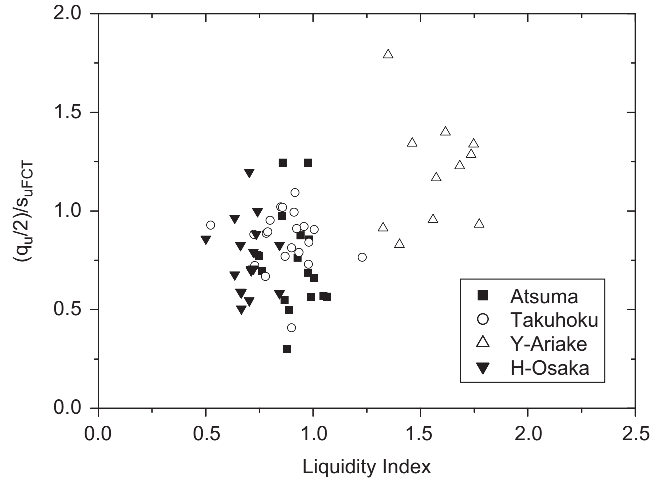



Fig. 3. Influence of liquidity index on the strength ratio.

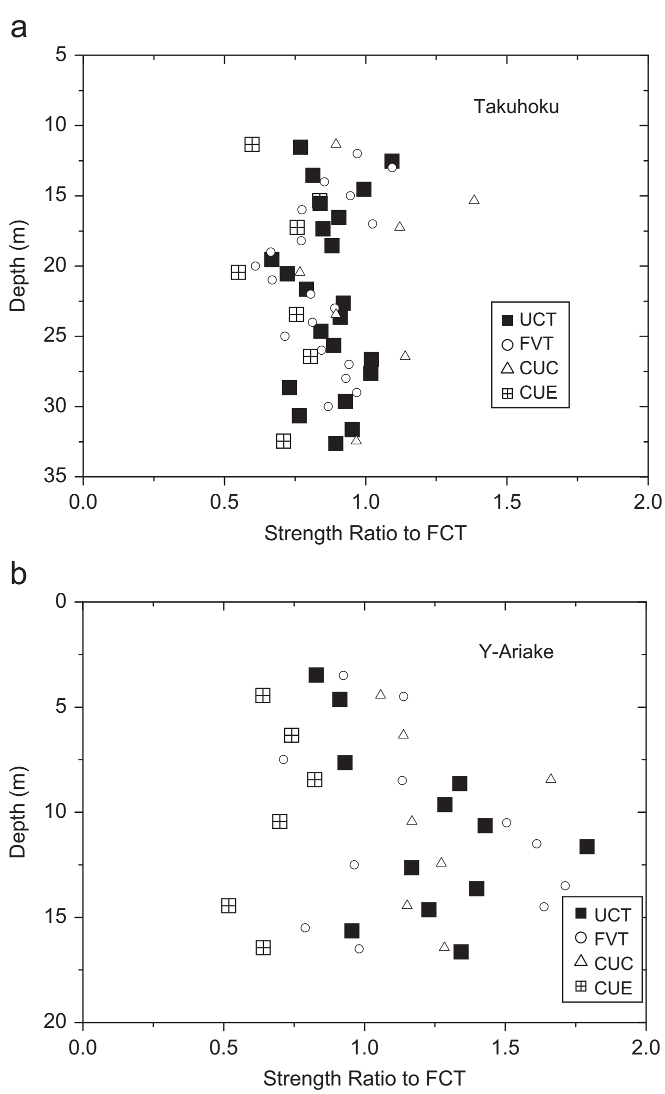



Fig. 4. Strength ratios to FCT, measured by various tests (a) Takuhoku site, (b) Y-Ariake site.

carried out at this site. It can be seen from Fig. 5 that the $S_t$ value given by the FCT is considerably greater that that given by the FVT, and this difference is more prominent in the Y-Ariake clay than for other clays, i.e., there is a 10

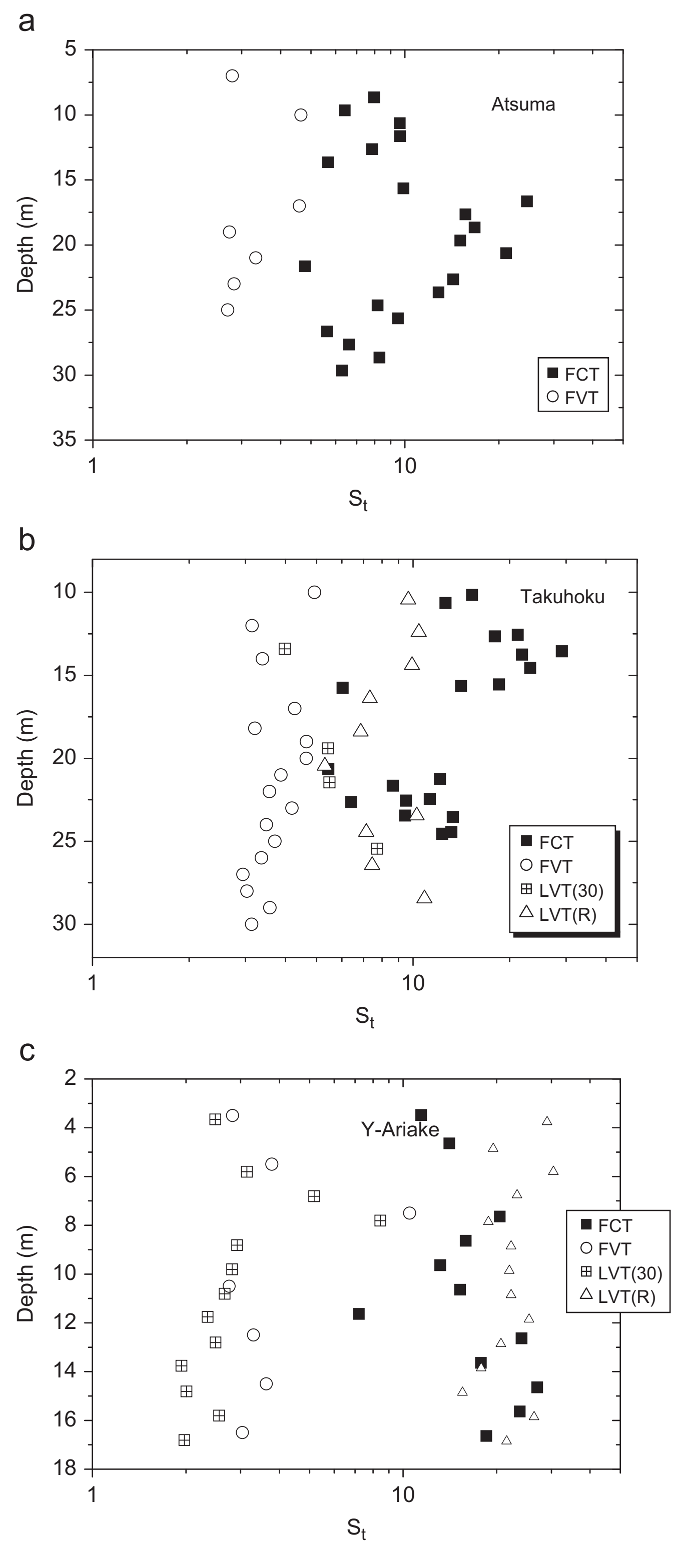
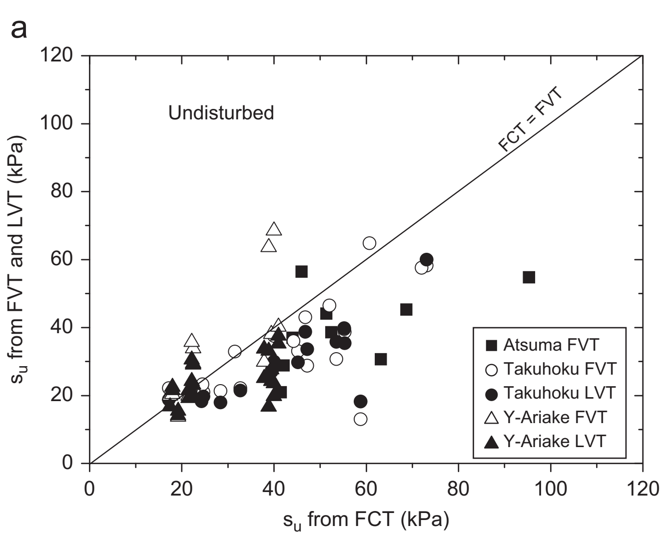



Fig. 5. Sensitivity measured by various methods (a) Atsuma site, (b) Takuhoku site, (c) Y-Ariake site.

fold difference in the $S_t$ values provided by the FCT and the FVT at the Y-Ariake site.

A reason for the different $S_t$ values given by the FCT and the FVT may be the difference in the peak or remolded strength measured by the FCT and the FVT. A comparison of the strengths measured by different testing methods is shown in Fig. 6, where (a) and (b) show the strengths at undisturbed and remolded states, respectively. As shown in Fig. 6(a) for undisturbed conditions, $s_u$ measured by the FCT is somewhat greater that that given by the FVT, except for the Y-Ariake clay. This result is consistent with Fig. 2, showing that $s_{uFCT}$ is greater than $q_u/2$, because the $q_u/2$ value and $s_u$ measured by the FVT are nearly the same for Japanese marine clays (for example, Tanaka, 1994). In addition to the FVT, at the Takuhoku and Y-Ariake sites, the LVT was also carried out. Tanaka (1994) has indicated that $s_u$ from the LVT and the FVT is nearly the same, and the test results from the Takuhoku site are consistent with his results. However, the distribution of $s_u$ at the Y-Ariake site measured by the FVT and the LVT is different: i.e., $s_u$ from the FVT is greater than that from the FCT, but $s_u$ from the LVT is smaller than that from the FCT. As a result, the ratio of strengths measured by the FCT and the FVT ranges between 0.3 and 1.5, but this difference in strength does not explain the large difference in $S_t$ measured by the FCT and the FVT. As shown in the comparison of the remolded strength ($s_{ur}$) in Fig. 6(b), the remolded $s_u$ from the FVT ($s_{uFVT30}$), which is measured after 30 tunes of the vane, is considerably greater than $s_u$ from the FCT ($s_{urFCT}$), where the sample is remolded by kneading. This trend is the same as $s_u$ from the LVT ($s_{uLVT30}$), where the remolded strength is obtained at 30 turns of the vane after measuring the peak strength. However, if the sample is kneaded in the same way as the FCT, the remolded strength measured by the LVT ($s_{urLVT}$) is in the same order of the remolded strength from the FCT. This fact indicates that the difference in the remolded strengths can be mainly attributed to the remolding methods, i.e., turning or kneading, but not by different shear mechanisms of the testing methods, i.e., using the vane or the cone. Remolding by 30 turns is not enough to reach the equivalent condition of kneading for 5 min by hands.



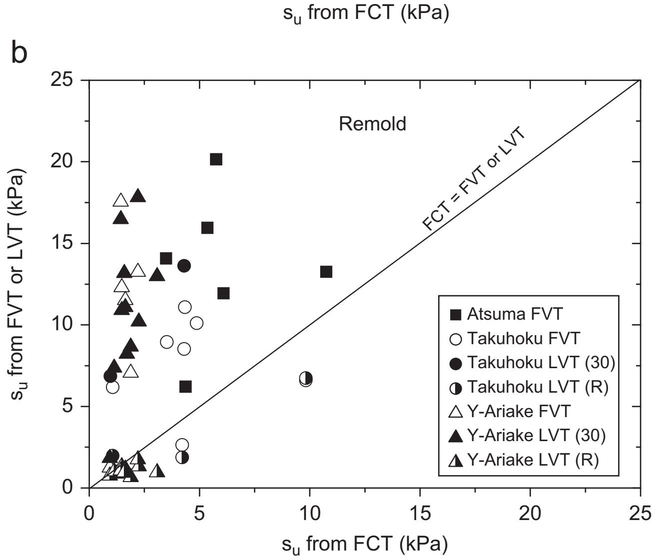




Fig. 6. Comparison of strengths measured by FCT, FVT and LVT at undisturbed and remolded conditions (a) undisturbed condition, (b) remolded condition.

## 6. Remolded strength

The definition of the remolded strength ($s_{ur}$) may be the minimum strength with the same void ratio or the same water content if the specimen is saturated. Since the value of the undrained shear strength depends on the effective stress and structure before shearing, it is reasonable to assume that the reduction of $s_u$ due to remolding is caused by the loss of effective stress and structure. In other words, the remolded state is the condition in which the sample holds the minimum effective stress and the lowest structure.

The $s_{ur}$ value has been studied by many researchers and correlated to fundamental parameters, especially $I_L$. Fig. 7 shows the relation between $s_{urFCT}$ and $I_L$ with a relation proposed by Leroueil et al. (1983). For Takuhoku clay, two persons remolded samples and to distinguish them, the test results are indicated by different symbols, A and B. As can be seen in figure, no clear differences were found in these relations. This leads to the conclusion that neither human error nor difference in the human operators is of importance when using the remolding method adopted in this study.

It can be seen that most points obtained from this study are located at the right hand side of the line given by Leroueil et al., i.e., the $s_{urFCT}$ measured in this study is larger than theirs, with exceptions of some samples from the Takuhoku site. These samples were collected from depths between 15 m and 18 m, where $w_n$ and $w_L$ or $w_P$ considerably vary with depths because of containing a large amount of sand (see Fig. 1(b)). Thus, it can be considered that a sample measuring $w_L$ and $w_P$ is different

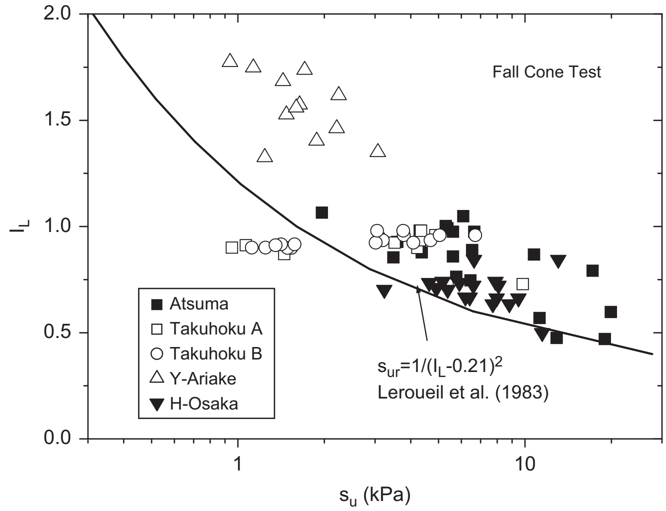



Fig. 7. Remolded strength from FCT relating to liquidity index.

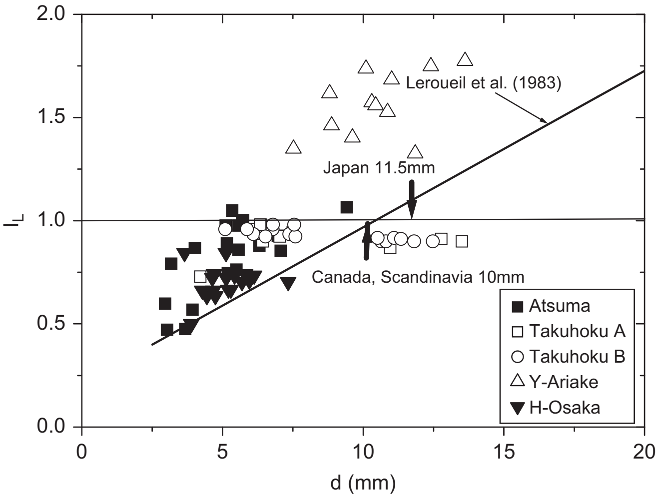



Fig. 8. Relation between penetration depth of the cone and $I_L$.

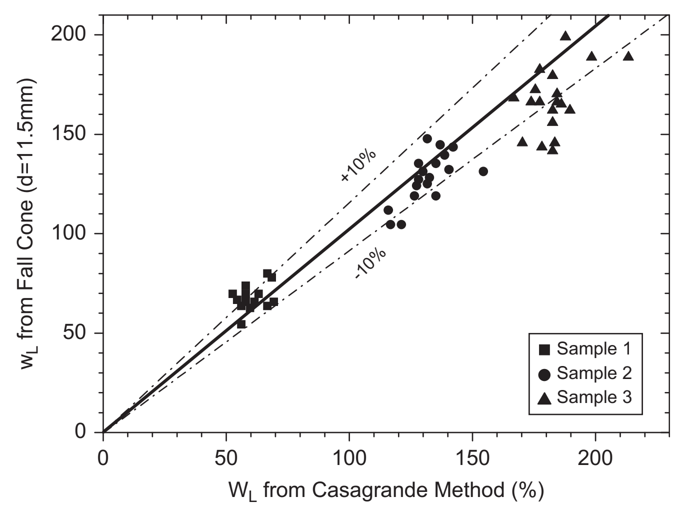



Fig. 9. Comparison of $w_L$ measured by FCT and Casagrande methods (after JGS, 2009).

from the sample measuring $s_{urFCT}$: i.e., the value of $I_L$ is not correct for these points.

Before considering for the discrepancy of the present study to Leroueils' line, it should be pointed out that the measurement methods for $w_L$ differ in Japan and Canada: i.e., in the present study, $w_L$ was measured by the Casagarande's method, while Leroueil et al. measured $w_L$ by FCT. Fig. 8 shows a direct correlation between $I_L$ and $d$, a penetration depth of the cone in FCT. For Leroueil et al.'s correlation, $d$ was calculated from Eq. (1). As already mentioned, the JGS has established a standard of $w_L$ using FCT, where the $d$ value adopted for $w_L$ in the standard is somewhat different from Canada and Scandinavian countries: i.e., $d$ at $w_L$ in these countries is 10 mm, while $d$ in the JGS standard is 11.5 mm. It is described in the JGS standard that the reason for adopting different $d$ from these countries is to obtain better correlation with the existed standard, i.e., using the cup according to Casagrande method. As seen in Fig. 9, which was obtained by the comparison study carried out by several organizations involving the establishment of this standard, $w_L$ measured by the Casagrande has better agreement with the FCT at a $d$ value of 11.5 mm, instead of 10.0 mm (JGS, 2009). However, it should be kept in mind that $I_L$ for the relation proposed by Leroueil et al. (1983) is calculated by $w_L$ which was measured by the FCT with 10 mm of penetration.

Tanaka et al. (2001b) compared $w_L$ for Louiseville clay, a Champlain clay, which is widely distributed in Quebec, Canada, measured by two different organizations: i.e., Port and Airport Research Institute (formerly Port and Harbor Research Institute, PHRI) and the geotechnical group at Laval university (La Rochelle et al., 1988; Hamoushe et al., 1995). As shown in Fig. 10, a difference of about 10% exists between the $w_L$ values measured by the two organizations. Of course, they used their own ways to measure $w_L$, i.e., the cup at PHRI and the fall cone at Laval university. Although the topics in this paper are not the determination of $w_L$, there is possibility that $w_L$ may be different according to the standards of different countries. Nevertheless, the most important finding in this study is that if $w_L$ is obtained by FCT at 10 mm of penetration following the Canadian standard, $I_L$ in Figs. 7 and 8 increases because $w_L$ decreases. That is, the measured points in Figs. 7 and 8 move upward and the difference between the present points and the Leroueils' line furthermore expands.

Another important finding in Fig. 8 is that samples with $I_L$ of 1.0 indicate much smaller $d$ values than 11.5 mm. Since at $I_L=1.0$, the water content of the sample is equal to $w_L$, $d$ should be 11.5 mm. This fact indicates that the remolded condition created by kneading the sample in this study is somewhat different from the conditions when $w_L$ is measured. In the practical way to prepare a specimen for measurement of $w_L$, a tested soil is not remolded by the type of kneading used in the present study, but rather ground and crushed using a knife. In this way, even small crumbs are completely destroyed and considered to be thoroughly uniform. Seng and Tanaka 2012 measured the undrained strength at $w_L$ by

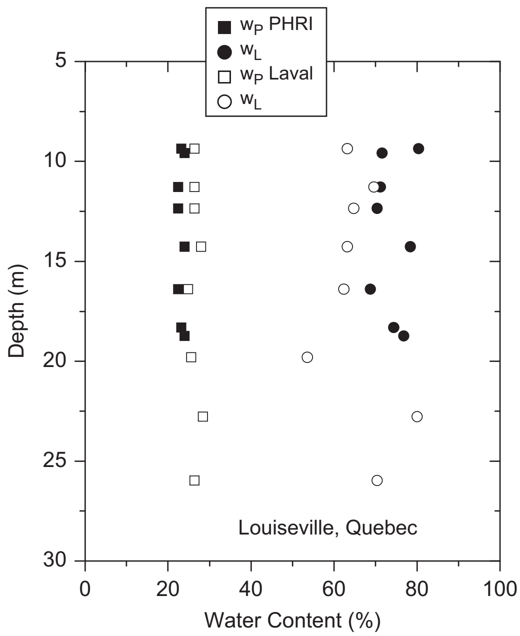



Fig. 10. Comparison of $w_L$ measured following Japanese and Canadian's standards (After Tanaka et al., 2001b).

laboratory vane and reported that $s_u$ at $w_L$ is ranged between 1 kPa and 2 kPa, which well corresponds to Leroueils' relation. They used a mixer for remolding sample so that the sample was more thoroughly remolded. Their results also indicate the importance of the remolding method.

## 7. Conclusions

In this study, the applicability of the fall cone test (FCT), which is a simple mechanical test in geotechnical engineering, to measurement of the undrained strength for design and the sensitivity has been examined. The main conclusions are as follows:

1) The undrained shear strength ratio obtained by the FCT and the unconfined compression test (UCT) differ considerably for various soils. Although it is not clear exactly which factors determine the difference, the undrained shear strength measured by the FCT cannot be used as an equivalent strength measured by the UCT.
2) Sensitivity, which is the undrained strength ratio of undisturbed and remolded conditions, was obtained by the FCT, and the field and laboratory vane test (FVT, LVT, respectively). The sensitivity measured by these methods differed considerably, with as much as a 10 fold difference in the sensitivity given by the FCT and the FVT. The main factor contributing to this large difference is the remolding method. The turning of the vane in the FVT is not equivalent to the remolded conditions for the FCT, which is created by kneading by hand.
3) Even the remolded condition created by kneading by hand is not equivalent to conditions for the measurement of the liquid limit test using the cup. This may be attributed to the main reason for discrepancy between published data previously and the presented data. The remolding methods for measurements of sensitivity need to be rigorously defined.

Finally the authors want to emphasize the difference in testing method for the determination of the liquid limit ($w_L$) using the Fall cone test between Japan and other countries, although this matter is not directly correlated to the present study. It is urgent that these discrepancies are addressed and a unified method is agreed upon for the determination of $w_L$ to avoid unnecessary confusion.

## Nomenclature

*Testing method*

FCT fall cone test
FVT field vane test
LVT laboratory vane test
LVT(R) laboratory vane test for remolded sample by kneading
LVT(30) laboratory vane test for remolded sample by 30 turns
UCT unconfined compression test

*Undrained shear strength*

$q_u/2$ half of the unconfined compression strength
$s_u$ undrained shear strength
$s_{uFCT}$ undrained strength from an intact sample
$s_{uFVT}$ undisturbed strength measured by FVT
$s_{uFVT30}$ remolded strength by FVT after 30 turns
$s_{uLVT}$ undisturbed strength measured by LVT
$s_{uLVT30}$ remolded strength measured by LVT after 30 turns
$s_{ur}$ remolded strength
$s_{urFCT}$ remolded strength measured by FCT (The sample was kneaded)
$s_{urLVT}$ remolded strength measured by LVT (The sample was kneaded)
$s_{um}$ mobilized undrained shear strength

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